

Pressurization of a Flightweight, Liquid Hydrogen Tank: Evaporation & Condensation at a Liquid/Vapor Interface



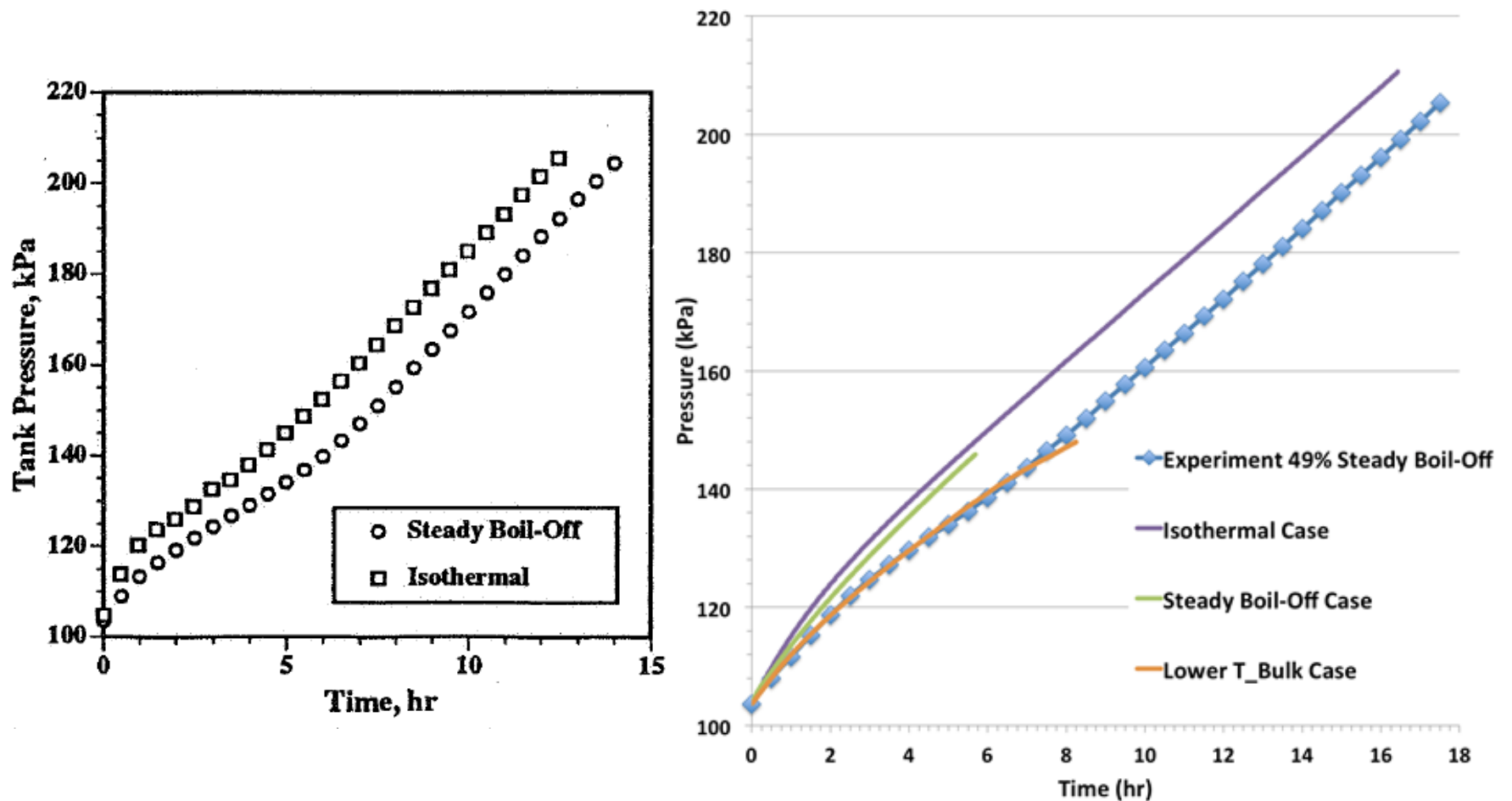
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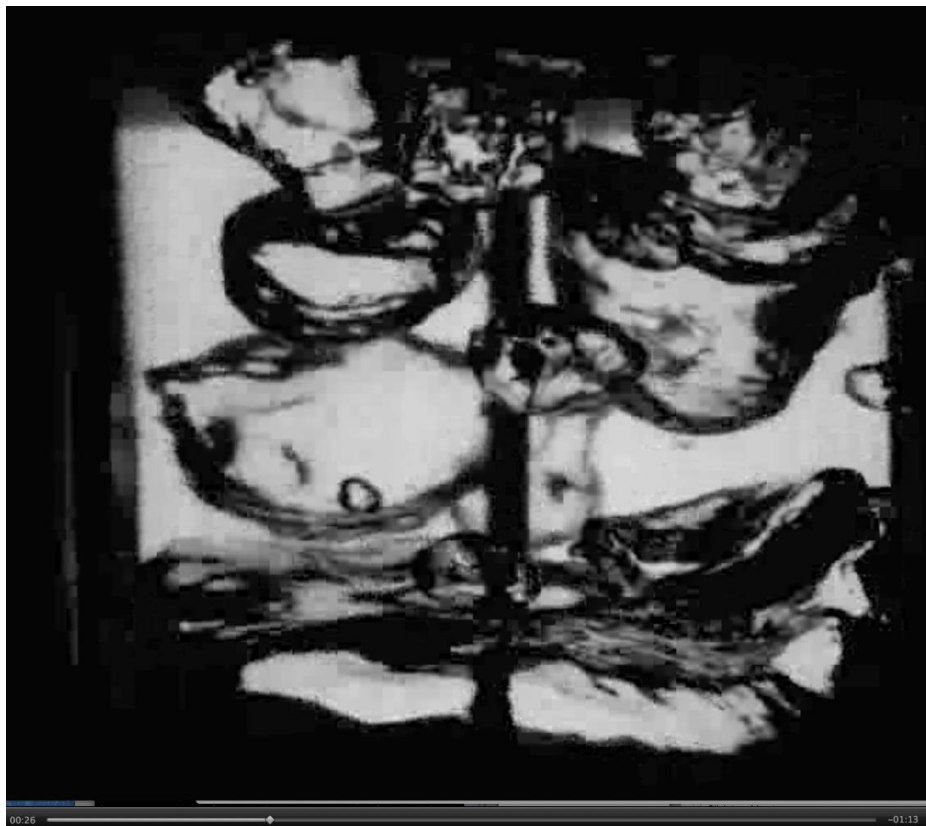
Outline

- Issues with evaporation/condensation at interface
- Temperature jumps at an interface—sharp gradients
- Interface physics: mass and *energy* transfer
- Model equation: solved two ways
- Numerical methods: subgrid model & coupling
- Results: practical demonstration of method

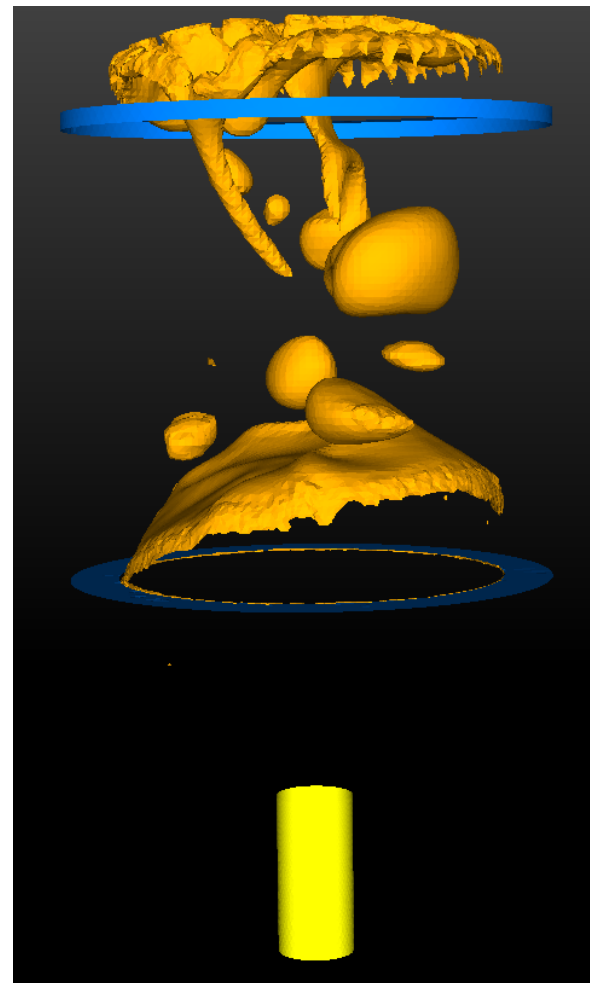
K-Site: Slow Self-Pressurization Captures Pressure Evolution



CNES Low-g Slosh: Heavy Boiling Phase with Condensation and Transit



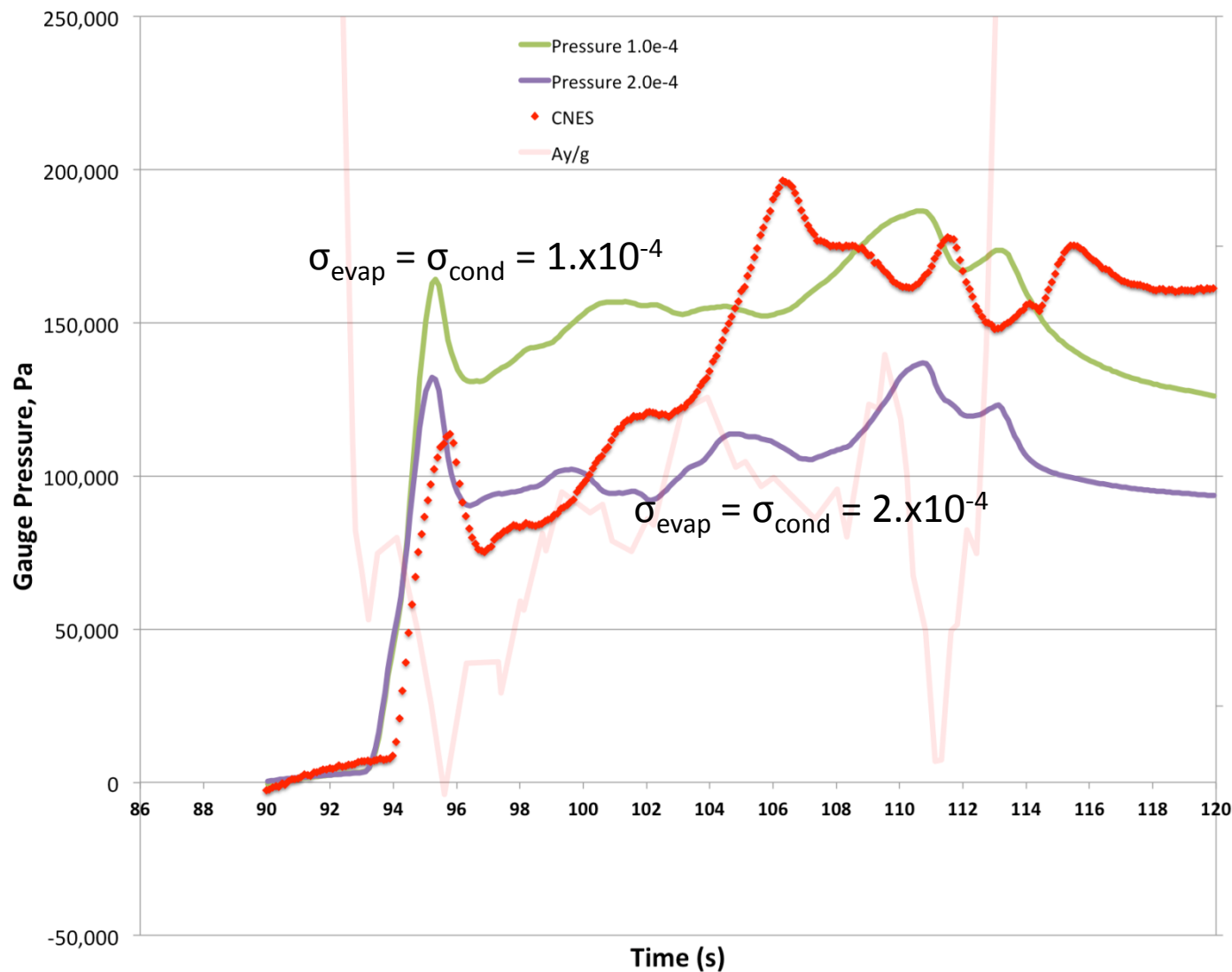
00:26 in data



T=96.75 s in CNES_5C_7



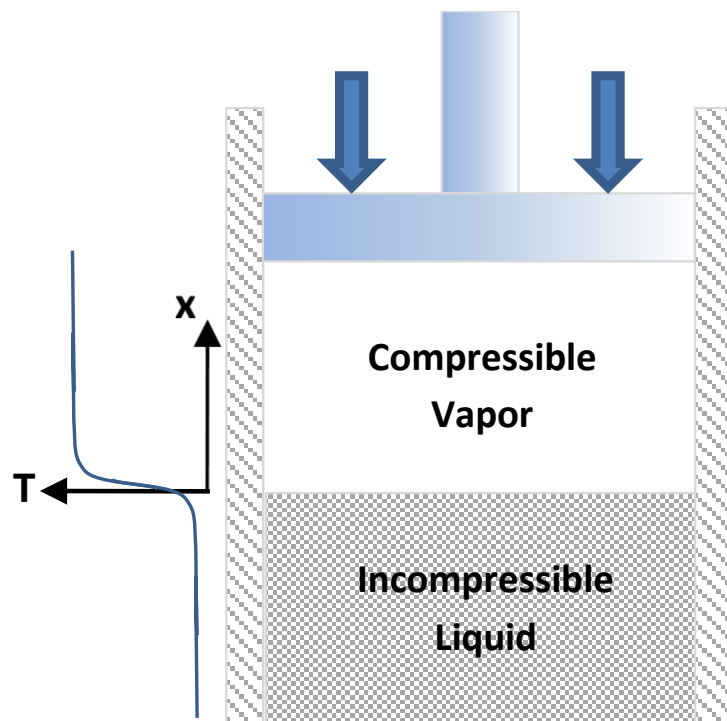
CNES Low-g Slosh: Pressure Evolution



Temperature “Jumps” at the Interface

$$W = - \int p \, dV$$

Work done on the vapor phase



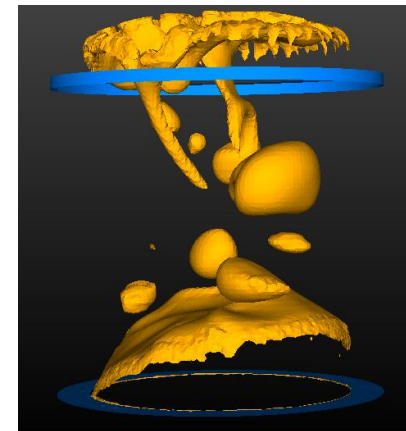
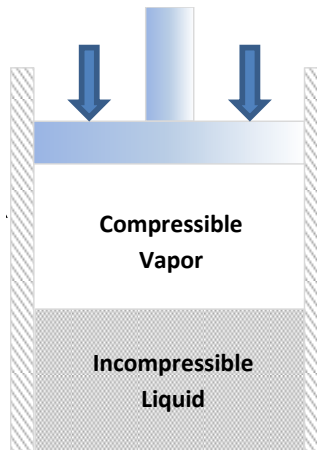
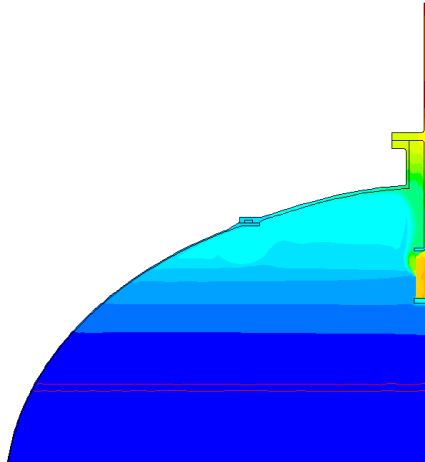
Pressurization caused by:

- Pressurant
- Boiling liquid
- Clouds rise/fall
- Temperature gradients

Temperature gradient
established

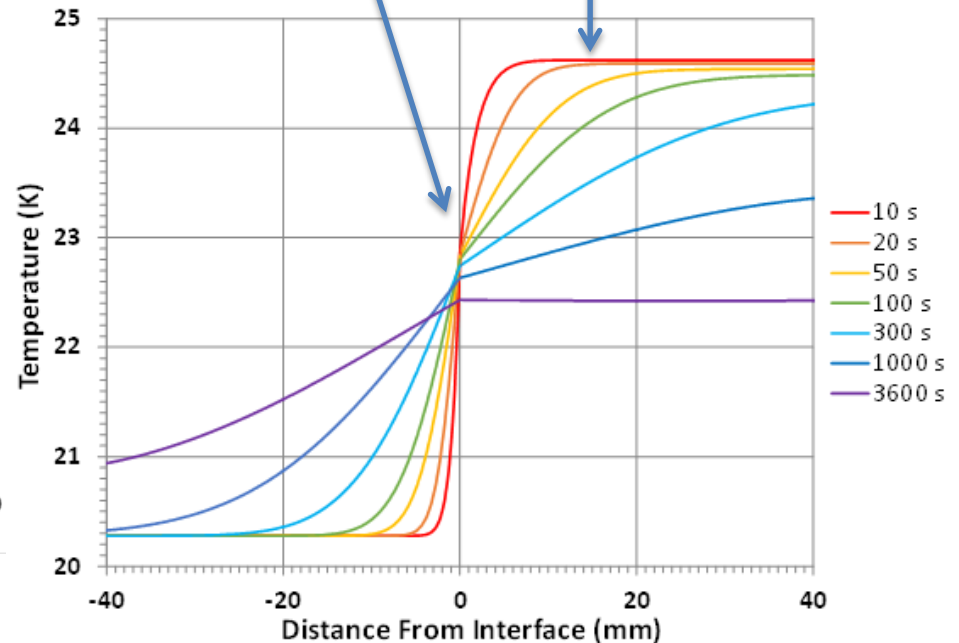
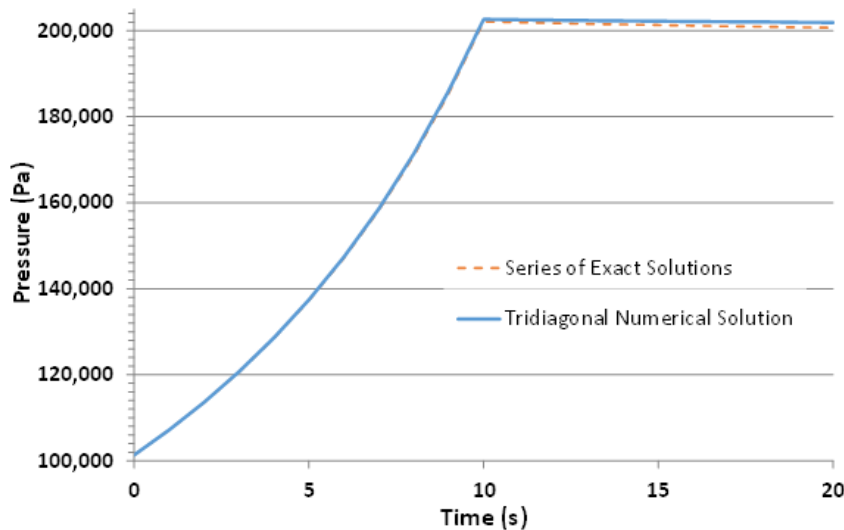
Pressurization of a Compressible Gas

	Latent Heat ΔH_{vap} (J/kg)	T_{sat} (K)	$\Delta T_{compress}$ $1 \rightarrow 2 \text{ atm}$ (K)	Vapor $\Delta H_{vap}/C_p$ (K)	Liquid $\Delta H_{vap}/C_p$ (K)	Vapor α	Liquid α
Helium	20,752.	4.2304	1.342	2.3	3.9	5.95E-05	2.82E-05
Methane	510,830.	111.67	20.433	230.3	146.7	2.88E-03	1.25E-04
Nitrogen	199,178.	77.355	16.942	177.2	97.6	1.45E-03	8.86E-05
Oxygen	213,050	90.188	19.752	219.5	125.4	1.93E-03	7.82E-05
Parahydrogen	445,440.	20.277	4.441	36.4	46.1	1.04E-03	2.81E-06
Water	2,256,440.	373.12	70.019	1084.9	535.3	2.02E-02	1.68E-04



Energy/Heat Equation

$$\rho C_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} = \dot{q}_{interface} + \dot{q}_{vap} \quad \alpha = \frac{k}{C_p \rho}$$



Negligible:

- Fluid motion
- Temperature variation in interface plane



Heat Equation: Series of Exact Solutions

$$\rho C_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} = \dot{q}_{interface} + \dot{q}_{vap}$$

$$T^{vap}(x, t) = T_{\infty}^{vap}(t) + \sum_{j=1}^{t_j \leq t} \frac{Q_j^{vap}}{(4\pi\alpha_{vap}(t-t_j))^{1/2}} e^{\frac{-x^2}{4\alpha_{vap}(t-t_j)}}, \quad x \geq 0$$

$$T^{liq}(x, t) = T_{-\infty}^{liq} + \sum_{j=1}^{t_j \leq t} \frac{Q_j^{liq}}{(4\pi\alpha_{liq}(t-t_j))^{1/2}} e^{\frac{-x^2}{4\alpha_{liq}(t-t_j)}}, \quad x \leq 0$$

$T_{-\infty}^{liq}$, is assumed constant

$T_{\infty}^{vap}(t)$, from isentropic compression $\frac{T_1}{T_0} = e^{\frac{dS}{C_p}} \left(\frac{V_0}{V_1}\right)^{\gamma-1}$:

$$\left(-k_{liq} \frac{dT}{dx}\right)_{interface-liq} - \left(-k_{vap} \frac{dT}{dx}\right)_{interface-vap} = \dot{q}_{flux} = \dot{m}_{flux}(p_{interface}, T_{interface}) \Delta H_{vap}(T_{interface})$$



Heat Equation: Numerical Solutions

$$\rho C_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} = \dot{q}_{interface} + \dot{q}_{vap}$$

$$D(T_i^+ - T_i^-) - (T_{i+1}^+ - T_i^+) + (T_i^+ - T_{i-1}^+) + \frac{(\omega - 1)}{\omega} (T_{i+1}^- - T_i^-) - \frac{(\omega - 1)}{\omega} (T_i^- - T_{i-1}^-) = \frac{\Delta x^2}{\omega k} \dot{q}_{vap}$$

$$D = \frac{\rho C_p \Delta x^2}{\omega k \Delta t}$$

Solved as a tridiagonal matrix

$T_{-\infty}^{liq}$, is assumed constant

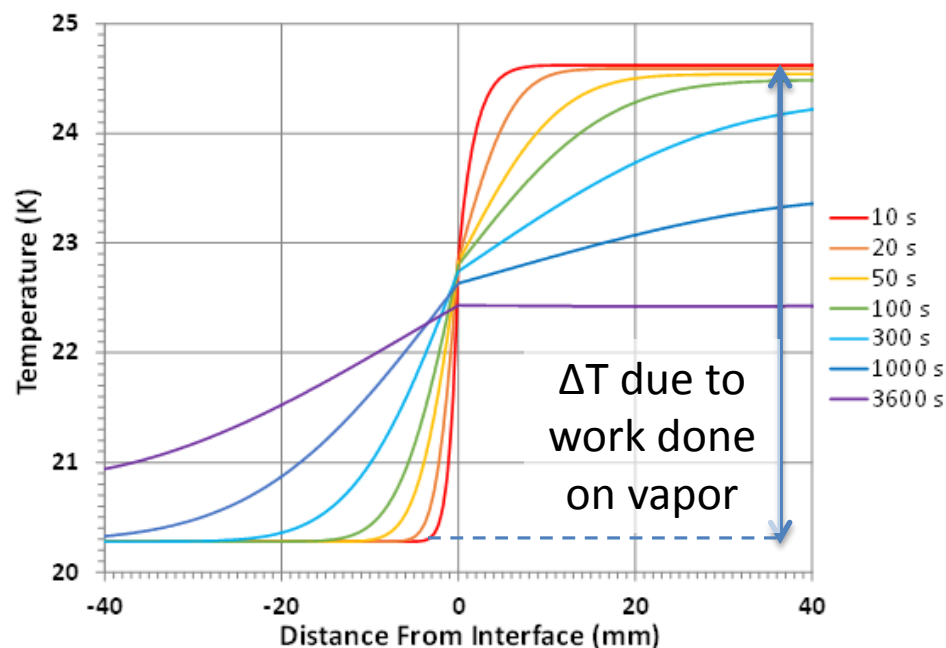
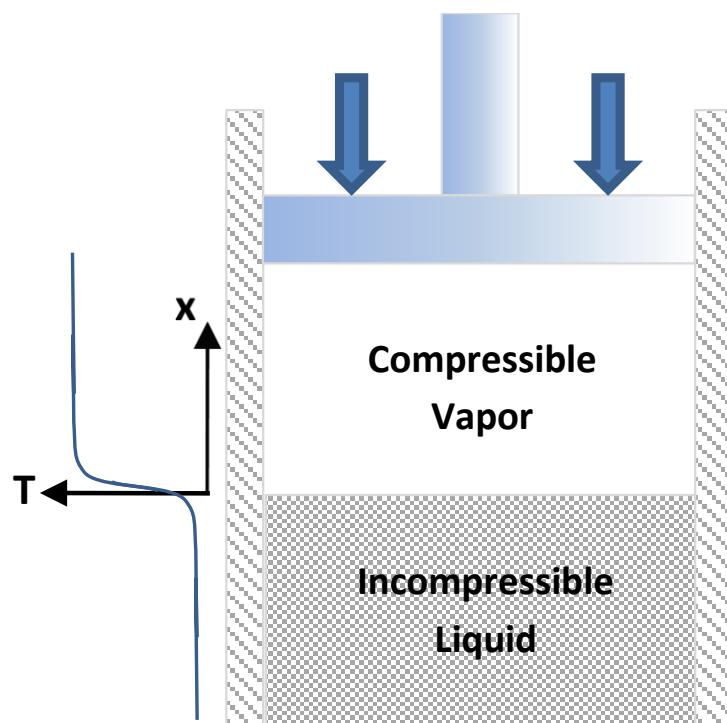
$T_{\infty}^{vap}(t)$, from isentropic compression

$$\frac{T_1}{T_0} = e^{\frac{dS}{C_p}} \left(\frac{V_0}{V_1} \right)^{\gamma-1} :$$

$$\left(-k_{liq} \frac{dT}{dx} \right)_{interface-liq} - \left(-k_{vap} \frac{dT}{dx} \right)_{interface-vap} = \dot{q}_{flux} = \dot{m}_{flux} (p_{interface}, T_{interface}) \Delta H_{vap}(T_{interface})$$

Temperature “Jumps” at the Interface

$$W = - \int p \, dV$$





~~Intermission~~ Mid-Review

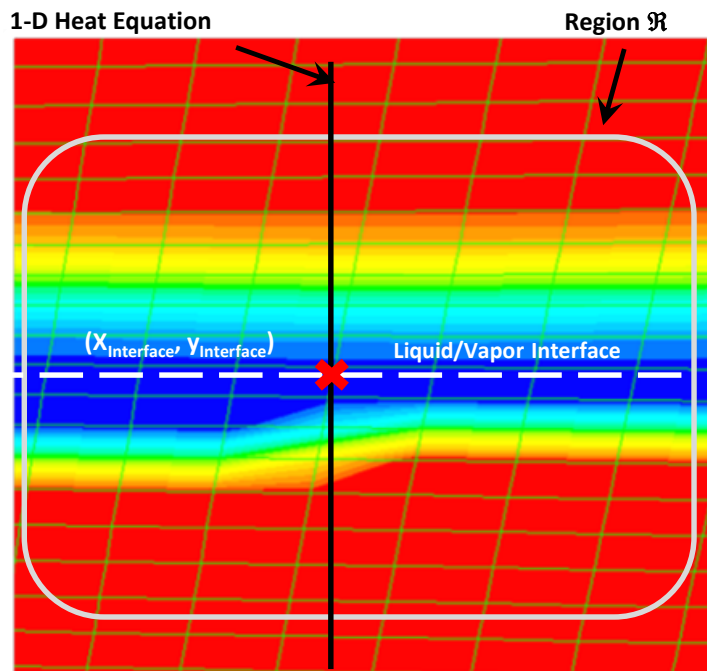
- Thermal Layers: role of heat near the interface
- Exact & numerical solutions: verification
- Evaporation/Condensation rates:
 - Temperature gradients at interface, $O(1 \text{ mm})$
 - Heat transfer near interface is important--
if not rate limiting
- From Physics, application to CFD
simulation \dashrightarrow



CFD: Subgrid Model for Interface

- Fine grid needed to resolve thermal layers $\sim 1\text{mm}$
- Interface can move and curve
 - grid generation nightmare, even unstructured, adaptive grid
- Subgrid model moves with the interface
- Solves the 1-D heat equation normal to interface
- Four couplings between subgrid model and Fluent
- Energy & mass source terms in liquid/vapor equations

Coupling Between Subgrid Model and Simulation



Coupling 1:

$$x_{\text{interface}} = \frac{\sum_{\mathcal{R}} x \varphi (1 - \varphi)}{\sum_{\mathcal{R}} \varphi (1 - \varphi)}$$

$$y_{\text{interface}} = \frac{\sum_{\mathcal{R}} y \varphi (1 - \varphi)}{\sum_{\mathcal{R}} \varphi (1 - \varphi)}$$

Coupling 2:

$$p_{\text{interface}} = \frac{\int_{\mathcal{R}} p \varphi_{\text{vap}} dV}{\int_{\mathcal{R}} \varphi_{\text{vap}} dV}$$

Coupling 3: Fluent Source Term $\dot{m}_{\text{interface}}$
(liquid & vapor)

Coupling 4: Fluent Source Term $\dot{q}_{\text{interface}}$
(liquid & vapor)

Mass and Energy are conserved

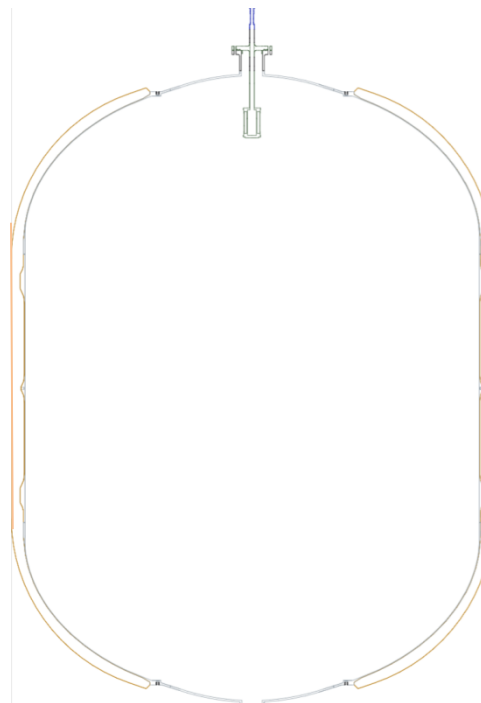
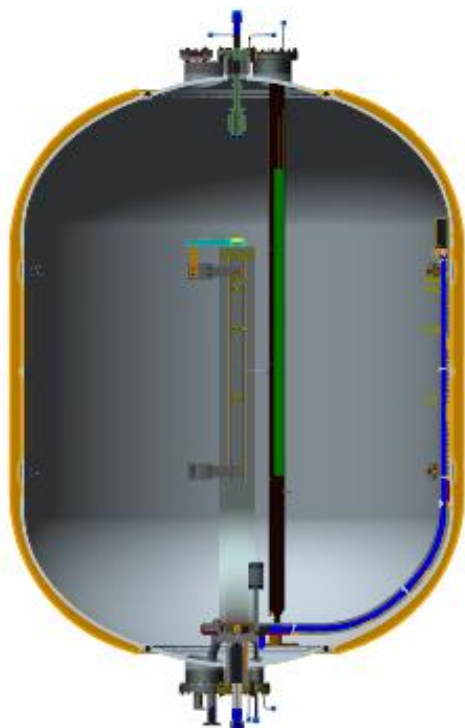
Must be careful about sizing Fluent source terms!!

EDU Tank



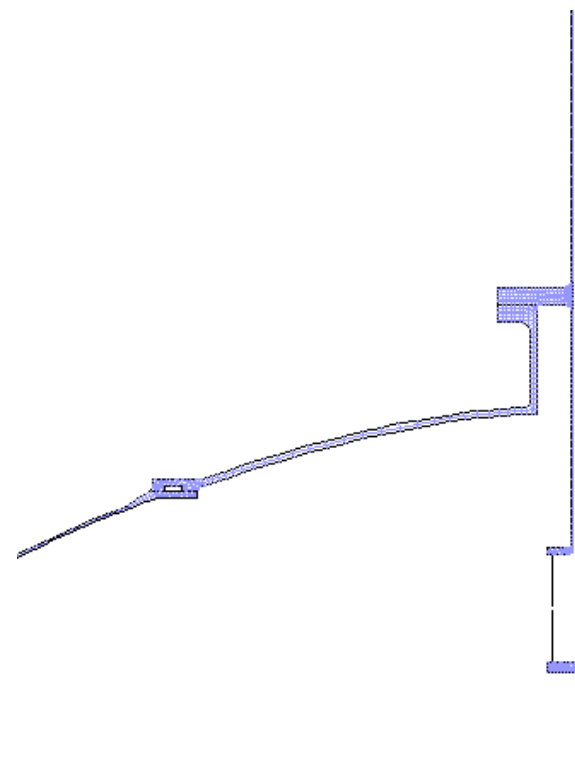
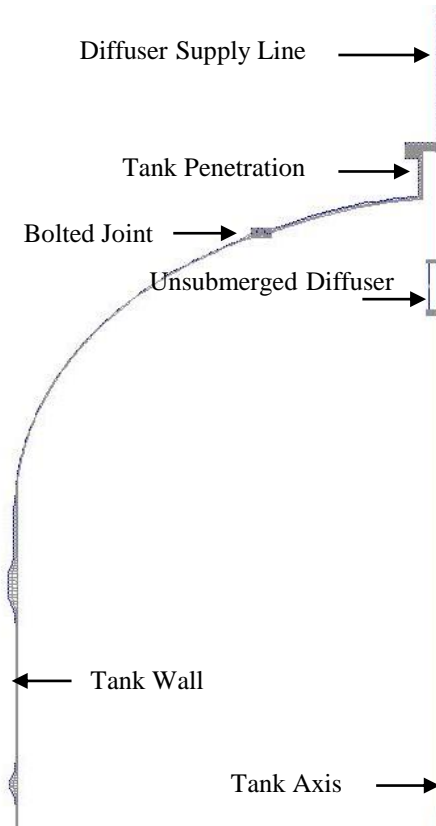
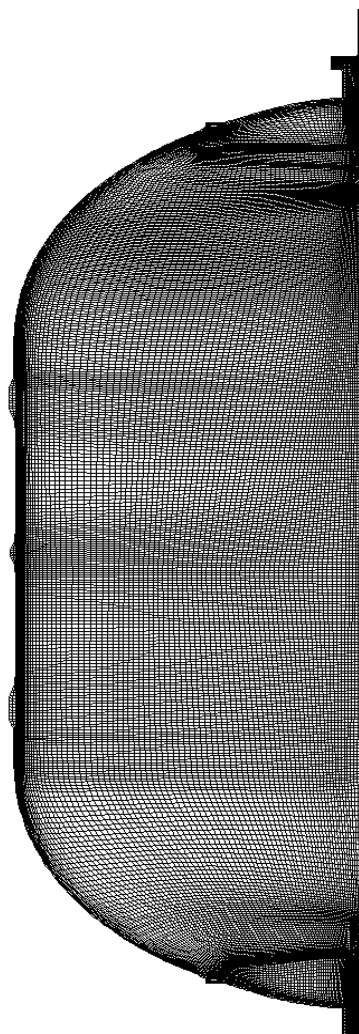
- 2219 Aluminum; Volume 4.34 m³; I.D. 1.70 m; I. H. 2.33 m
- 1.25" SOFI, 60 layers MLI; 2.54 mm wall thickness

EDU CAD Geometry



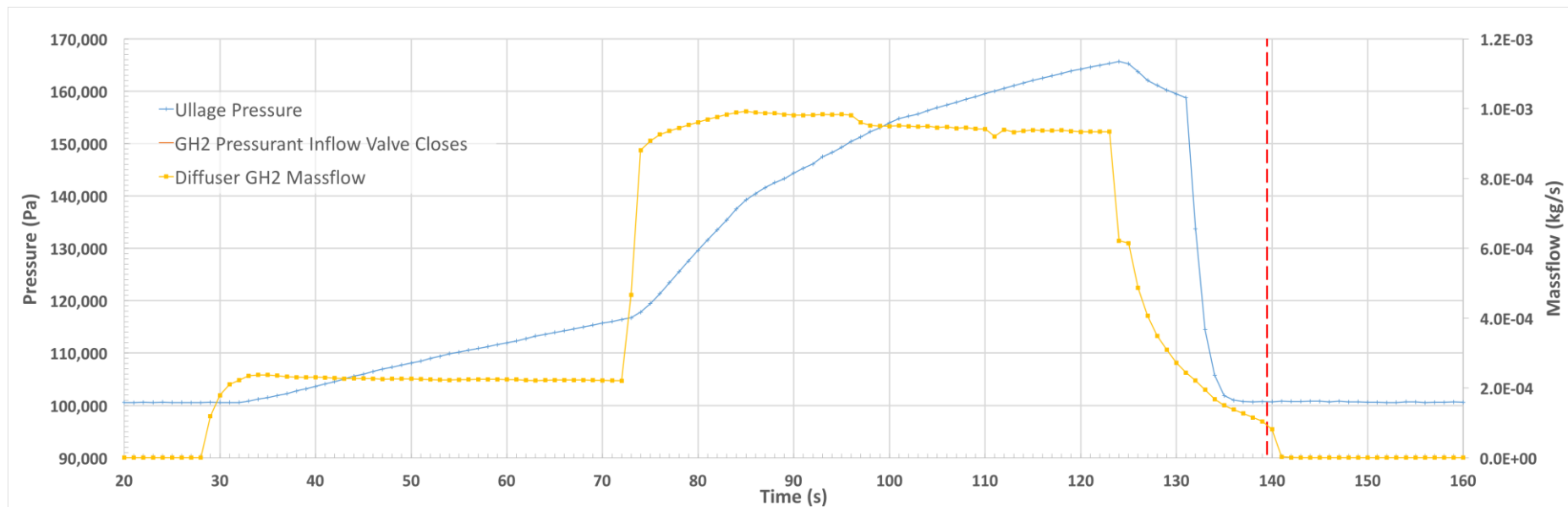
- Axisymmetric geometry/grid

EDU CAD Geometry

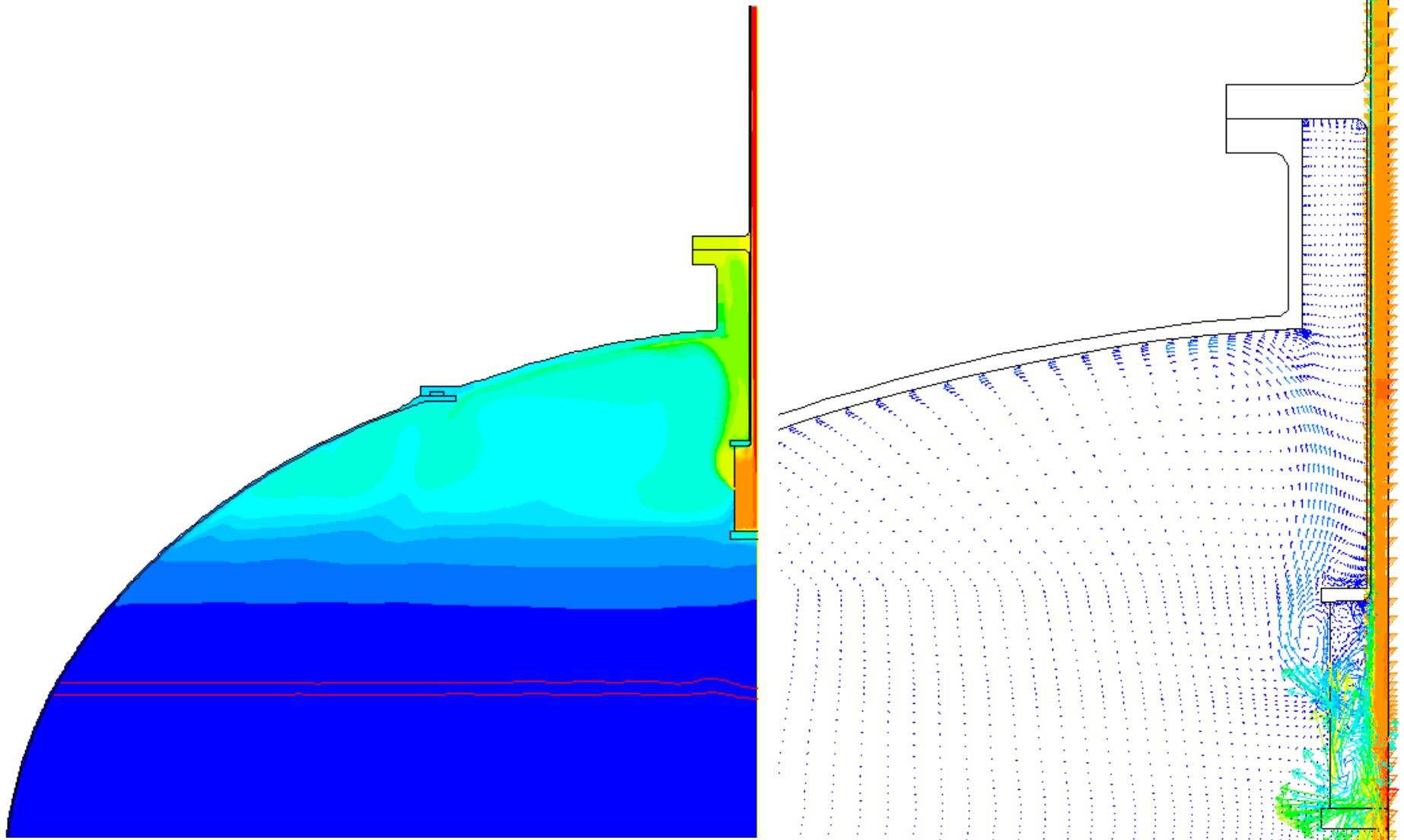


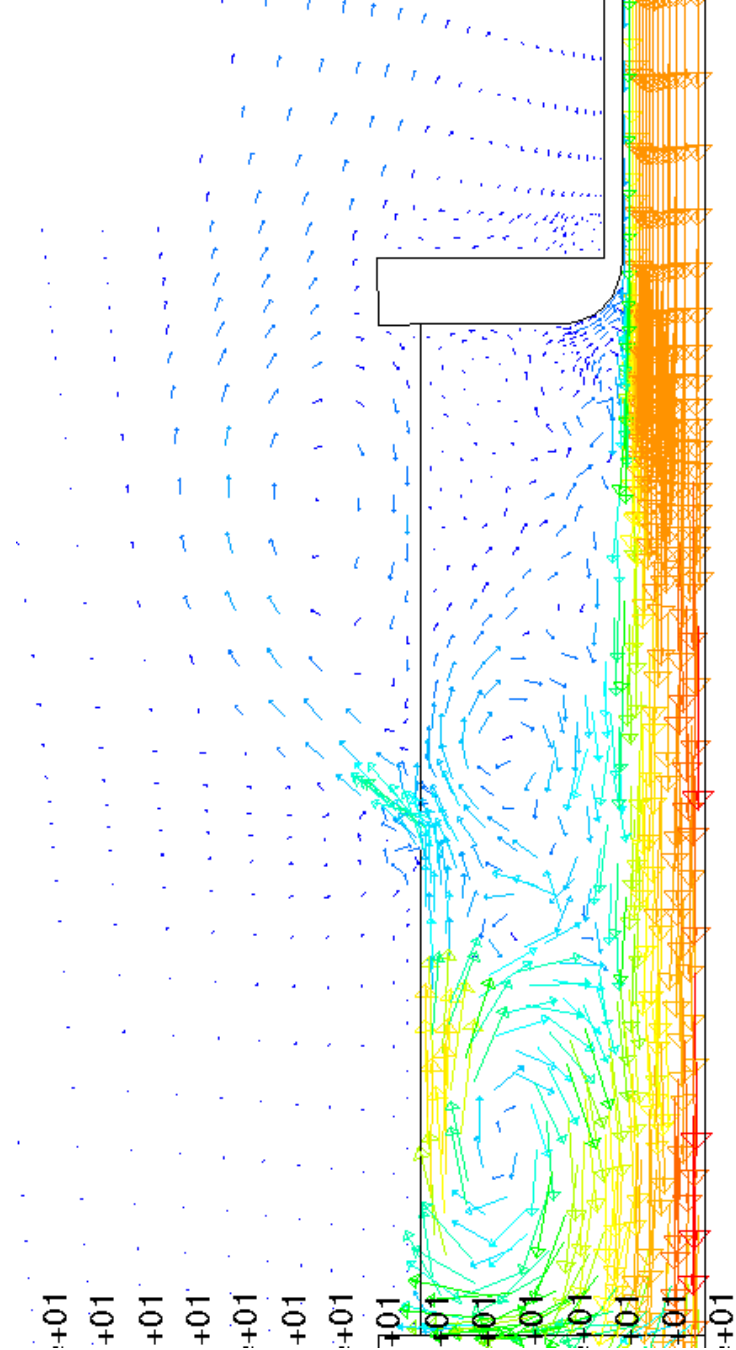
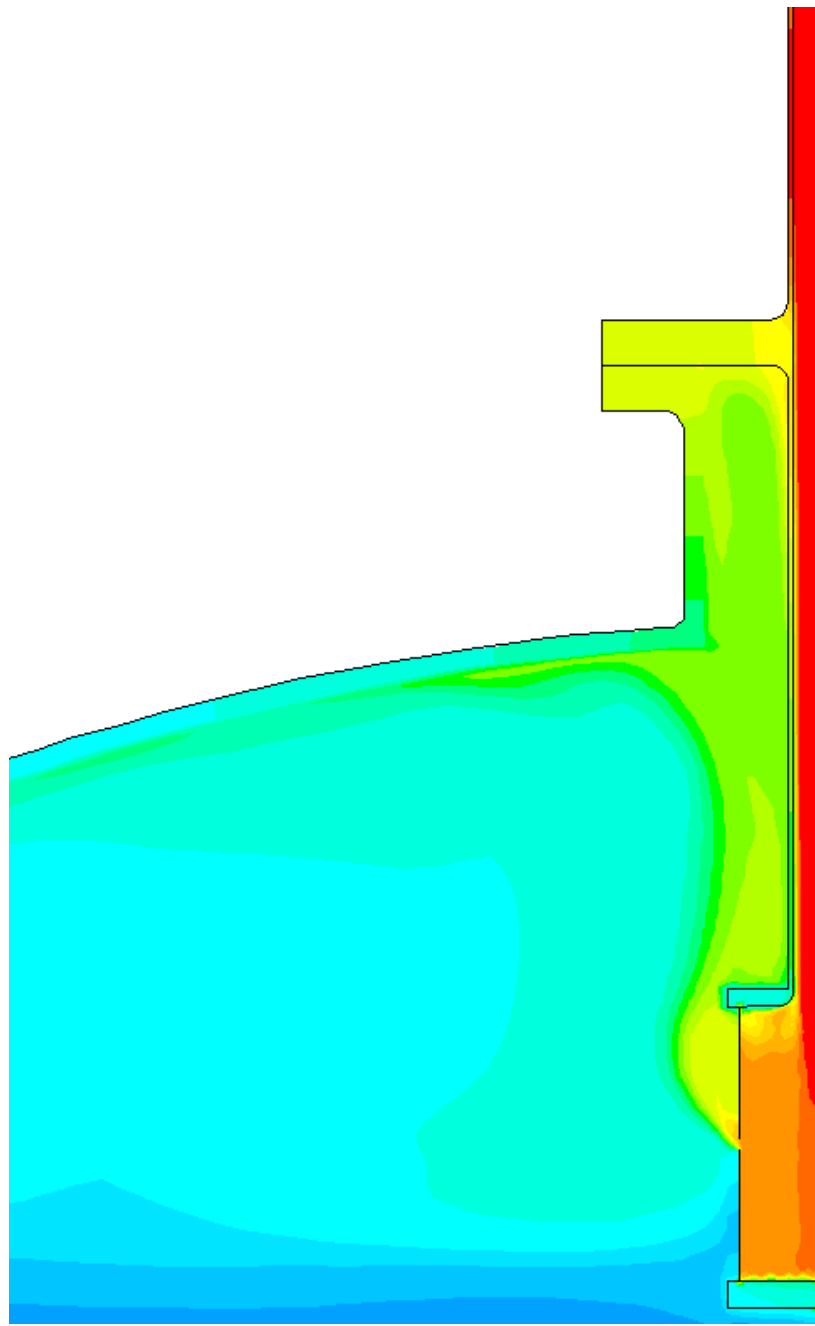


Phase A Test Data



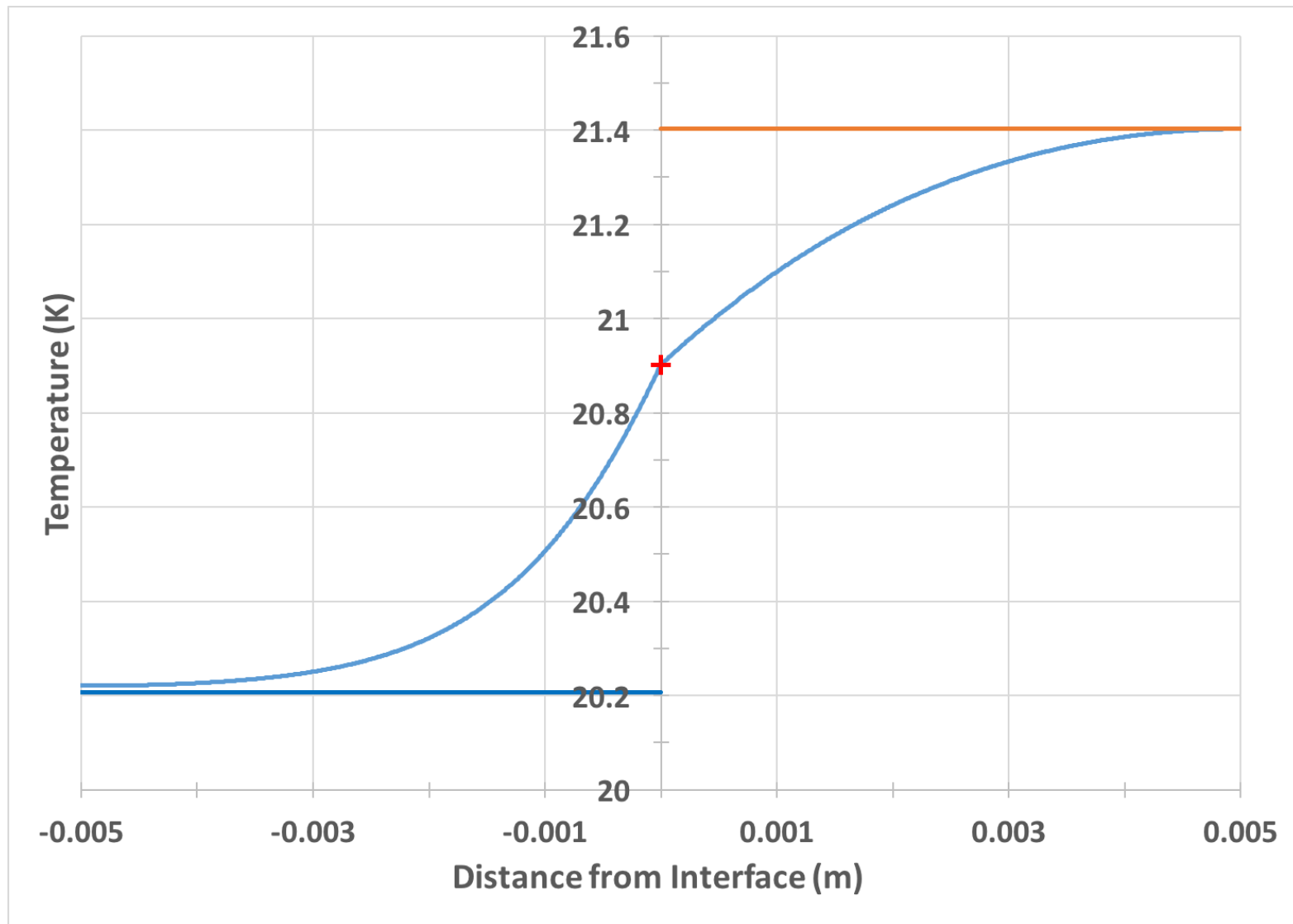
- Test HT-15, 16 on day 3 of Phase A testing
- 90% Fill level
- Pressurant gas at 290 K through the unsubmerged diffuser supply line
- Small drain flow, less than 1% of volume







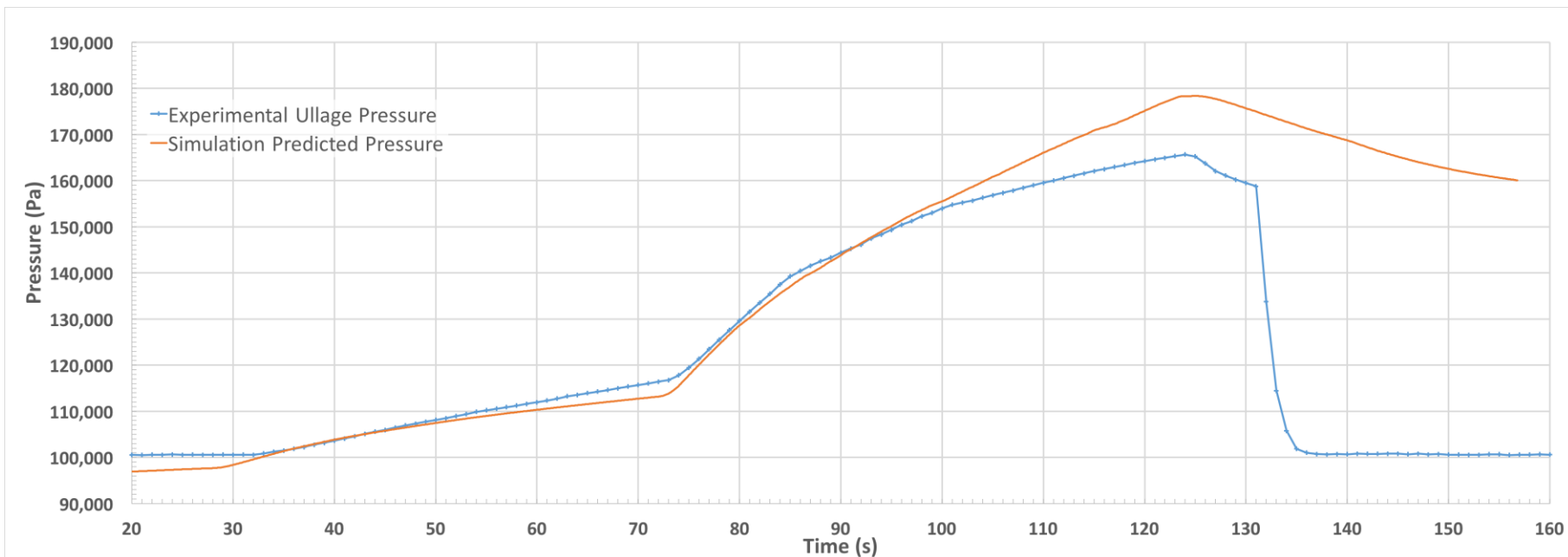
Press_11 at 87.23 seconds



$Q_{\text{vapor}} -4.04 \text{ W/m}^2$; $Q_{\text{liquid}} -54.03 \text{ W/m}^2$;

Condense Heat Flux 52.7 W/m^2 ; Condense Mass Rate $-1.13\text{e-}4 \text{ kg/m}^2\text{-s}$;

Results



- Good measure of condensation rate?
- For duration, pressurant inflow to condensation is between 1.5:-1 and 2:-1
- After 123 s, pressurant declines
- Assuming pressure release after 131 s



Conclusions

- Proof of concept for improved interface mass & energy transfer
- Accommodation coefficient of 1.0
- Extension to curved surfaces, multiple surfaces
- Need to examine other problems in the context of this result



Mass & Heat Equations

$$\rho C_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial x^2} = \dot{q}_{interface} + \dot{q}_{vap}$$

$$\dot{m}_{flux} (p_{interface}, T_{interface}) = \frac{2}{2 - \sigma_{cond}} \sqrt{\frac{MW}{2\pi R_u}} \left(\sigma_{evap} \frac{p_{sat}(T_{liq})}{\sqrt{T_{liq}}} - \sigma_{cond} \frac{p_{vap}}{\sqrt{T_{vap}}} \right)$$

$$\dot{q}_{flux} = \dot{m}_{flux} (p_{interface}, T_{interface}) \Delta H_{vap}(T_{Interface})$$

$$\frac{T_1}{T_0} = e^{\frac{dS}{C_p}} \left(\frac{V_0}{V_1} \right)^{\gamma-1} = e^{\frac{dS}{C_p}} \left(\frac{p_1}{p_0} \right)^{1-\frac{1}{\gamma}}$$